

Future Muon Magnetic Moment Anomaly

Measurements

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Proton Driver Workshop, October 2004 – FNAL

- Conclusion
- Experimental Method, Possible Improvements
  - $\times 10$  improvement at a new high flux facility
  - $< \times 2$  improvement(BNL proposal)
  - Current status
- Data/Theory Comparison: Case for a Future Run
- Theory Status- brief
- Introduction

## Outline

$$\mu_\mu = (1 + 0.001 \ 165 \ 165 \ 923) \frac{2m_\mu}{e\hbar} \text{ (500 ppb)}$$

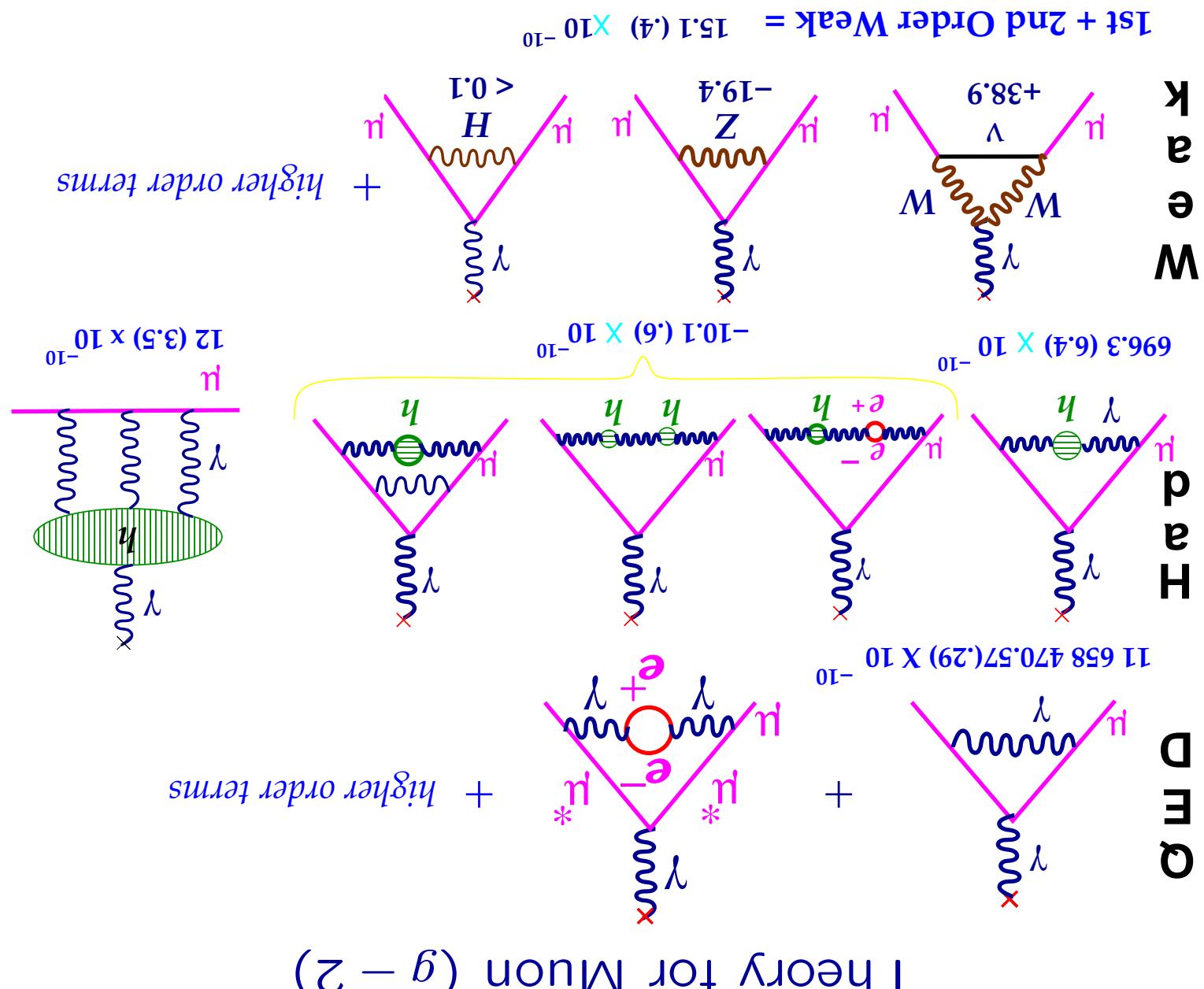
$$\mu_e = (1 + 0.001 \ 159 \ 652 \ 193) \frac{2m_e}{e\hbar} \text{ (4 ppb)}$$

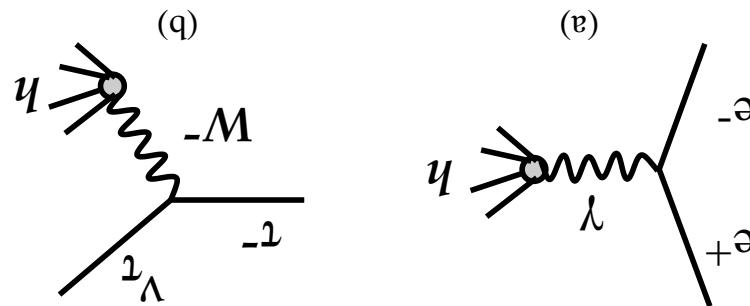
$$\mu = (1 + a) \frac{2m}{e\hbar} \quad \text{where } a = (\frac{g-2}{2})$$

For spin  $\frac{1}{2}$  particles,

$$\text{Magnetic: } \mu_s = g \left( \frac{2m}{e} \right) s$$

Magnetic Dipole moment: Definition

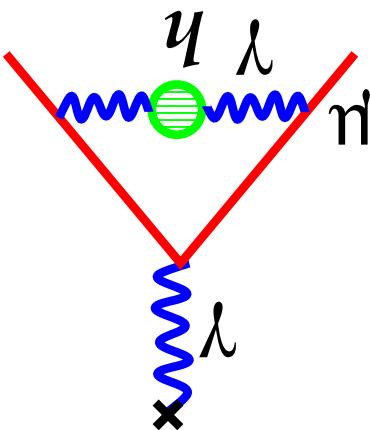




$$\Delta \mu(\tau^- \rightarrow \nu \tau \tau^- \pi^0) = 16.6(9.2) \times 10^{-10} \text{ (1.8 s.d.)}$$

$$\Delta \mu(\tau^- \rightarrow \nu \tau \tau^- \pi^0) = 694.4(7.2) \times 10^{-10} \text{ (2.9 s.d.)}$$

Determined from experimental data (low q loops) and/or QCD (high q loops), using  $R(s) = \frac{\sigma(e^- + e^- \rightarrow hadrons)}{\sigma(e^- + e^- \rightarrow \mu^+ \mu^-)}$  and:

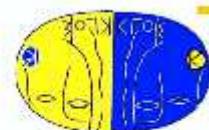
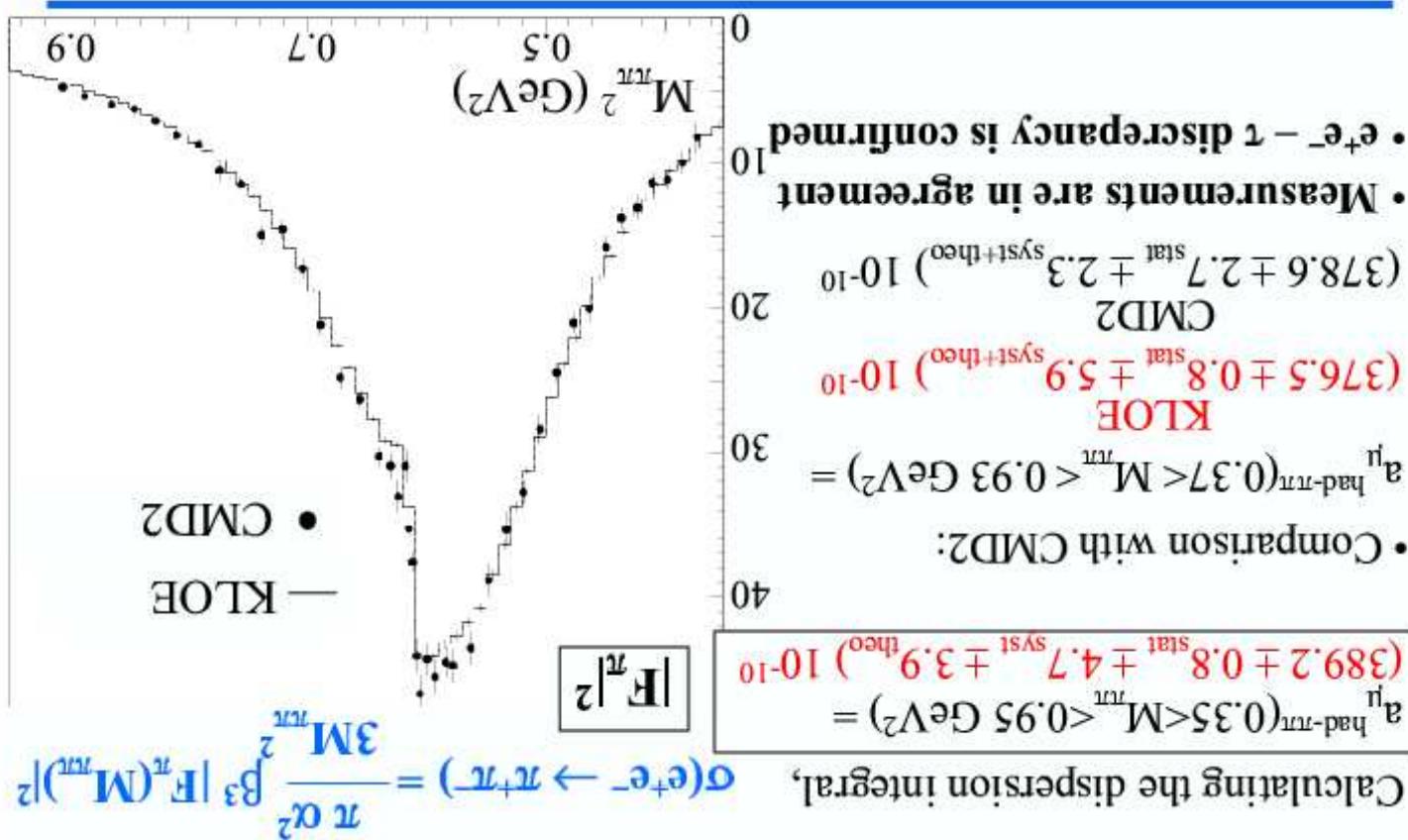
$$a_\mu(had; 1) = (\alpha m_\mu)^2 \int_{\infty}^{\infty} \frac{ds}{s^2} K(s) R(s)$$


$a_\mu(HAD; 1) = \text{LOWEST ORDER}$   
hadronic contributions

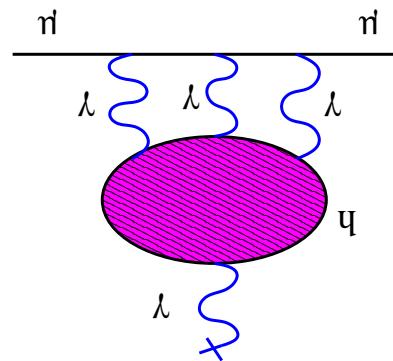
(provided by Juliet Lee-Franzini)

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Recent results from KLOE at DAΦNE - T. Spadaro - La Thulie, 5 March 2004

 $a_\mu^h - \text{Preliminary results}$

## Hadronic Light-on-light



Sighn change

Old:  $-8.5(2.5) \times 10^{-10}$   
New:  $+8.6(3.0) \times 10^{-10}$

Avg of: Hayakawa, Kinoshita PRD57(1998)465; Bijnen, Pallante,

Prades, NP B474(1996)379.

Sighn correction from: Knecht, Nyffeler, PRD65, 073034(2002).

Confirmed: Hayakawa, Kinoshita, hep-ph/0112102; Bijnen,  
Pallante, Prades, NP B626, 410(2002).

New Evaluation: Melnikov, Vainshtein, hep-ph/0312226

Adopted by Davier and Marciano:  $12.0(4.0) \times 10^{-10}$

Match short- and long-range behavior:  $13.6(2.5) \times 10^{-10}$

[1] M. Davier, W. Marciano, Ann. Rev Nuc. and Part. Phys. (2004)

$$\rightarrow 116\ 592\ 00.4(6.8) \times 10^{-10} \text{ (0.6 ppm)} \tau$$

$$\leftarrow 116\ 591\ 82.9(7.3) \times 10^{-10} \text{ (0.7 ppm)} e^+e^-$$

$$a_u(QED) = 116\ 584\ 72.07(0.11) \times 10^{-10} \quad a_u(EW) = 15.4(2) \times 10^{-10}$$

$$a_u(HAD;LBL) = 12.0(3.5) \times 10^{-10} \quad a_u(HAD;LBL) =$$

$$a_u(HAD;<1) = -9.8(0.1) \times 10^{-10} \text{ (no LBL)} \quad a_u(HAD;<1) =$$

$$a_u(HAD;1) = 711.0(5.8) \times 10^{-10} \text{ (\tau)} \quad a_u(HAD;1) =$$

$$a_u(HAD;1) = 694.4(7.2) \times 10^{-10} \text{ (e+e-)} \quad a_u(HAD;1) =$$

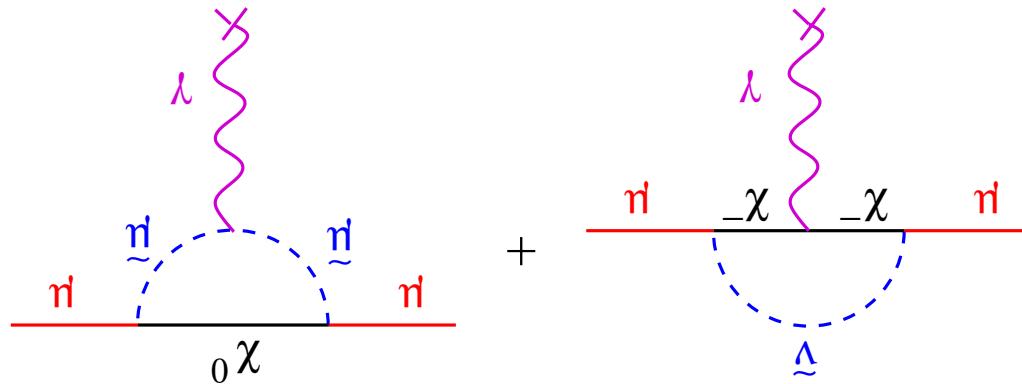
$$= 116\ 584\ 72.07(0.11) \times 10^{-10}$$

Standard Model Value for  $a_u$  [1]

- Now: 0.7 ppm Few years: 0.35 ppm Beyond: ???
- Future Outlook for Theory
- Novosibirsk (CMD2; VEP2000 and CMD3)
  - More  $e^+e^-$  data being analyzed over wider E range
  - VEP-2000 and CMD3 upgrades - better low E data and extend up to 2.0 GeV in 5-8 years
  - About to publish, fairly good agreement with shape, magnitude of Novosibirsk data
  - More data to analyze later
- ISR at KLOE: Dafne,  $e^+e^-$  up to  $\phi$  resonance
  - ISR at BABAR, CLEO, Belle:  $e^+e^-$  to higher energies Light-by-light: Lattice gauge efforts by two groups  $\tau$  Discrepancy: Under study by several groups

- $\Delta a_\mu^u \approx \left(\frac{m_u}{m_e}\right)^2$  ( $\times 4000$  more than electron)
- Sensitivity to New Particles:
- $\Delta a_\chi^u \approx \left(\frac{m_u}{\chi}\right)^2$
- Muon Substructure:

$$\Delta a_{SUSY}^u \approx 140 \times 10^{-11} \cdot \left(\frac{m}{100 \text{GeV}}\right)^2 \tan(\beta)$$



- Supersymmetry

$$\Delta a_{NEW}^u = a_{exp}^u - a_{theory}^u$$

$a_u^u$ : sensitive to all virtual particles coupling to muon

Search for "NEW" Physics

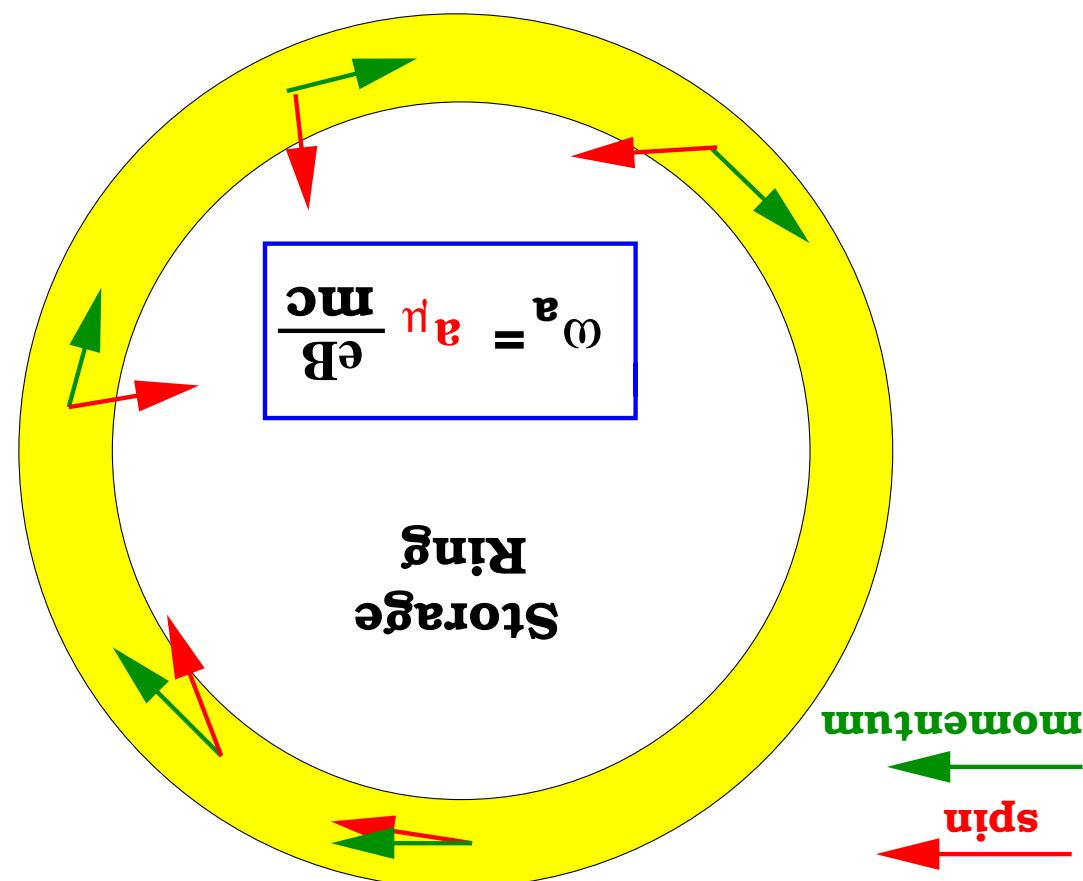
BNL E821-A New Precision Measurement of

Muon ( $g - 2$ )

→ Final results published Spring 2004 →

Boston University  
James Miller - Future Muon Magnetic Moment Anomaly Measurements  
Yale University  
KEK  
Tokyo Institute of Technology  
University of Minnesota  
Max Planck Institute für Med. Forschung - Heidelberg  
University of Illinois  
University of Heidelberg  
Groningen  
Cornell University  
Budker Institute - Novosibirsk  
Brookhaven National Laboratory  
Boston University

With homogeneous  $\vec{B}$ , all muons precess at same rate  
(exaggerated ~20x)  
Homogeneity → need less detailed knowledge of orbits  
Use Quadrupole electric field for focusing



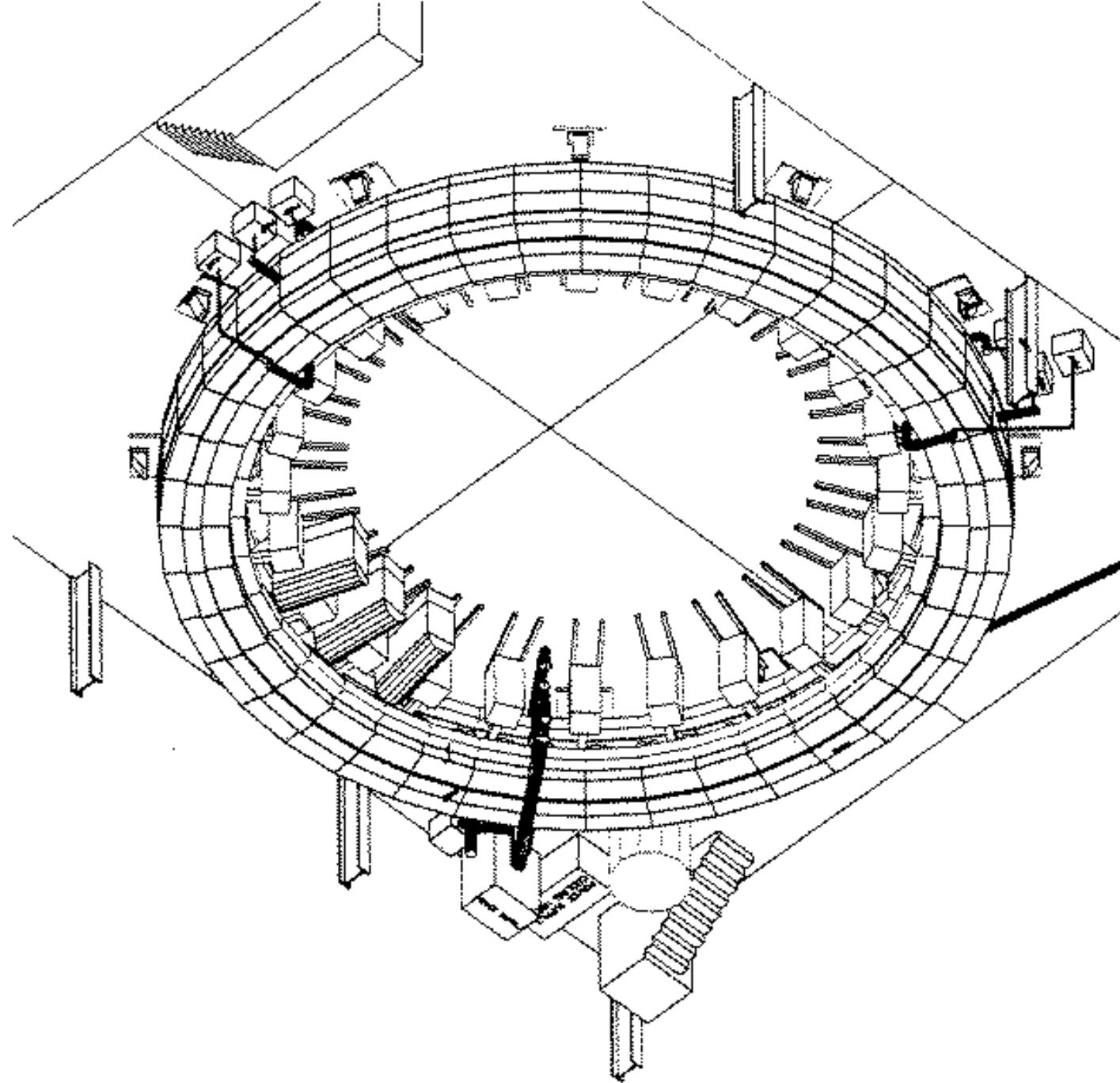
(Range of stored momenta:  $\approx \pm 0.3\%$ )

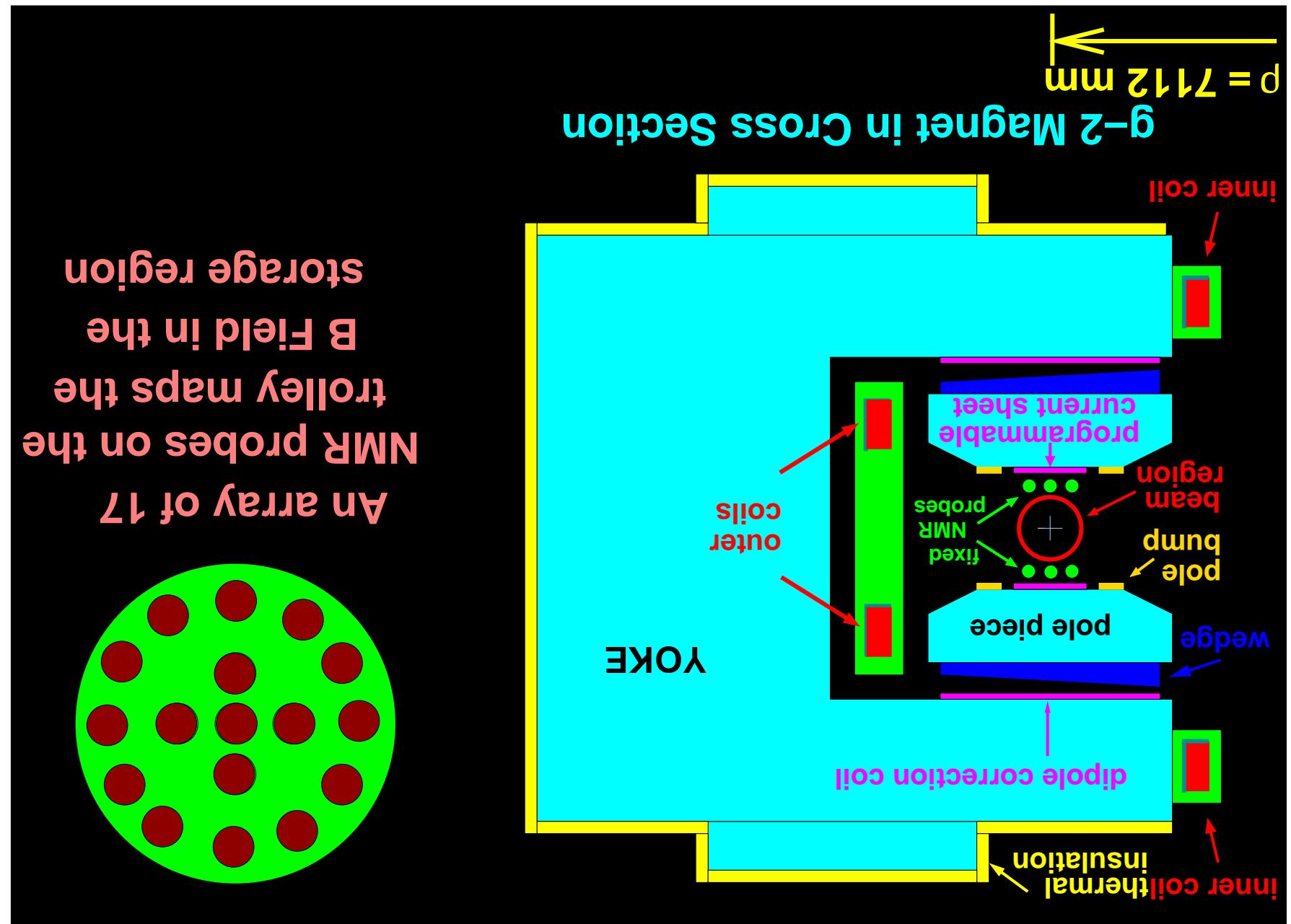
- $\gamma_T \approx 64.4\mu s$
  - $T_c \approx 149.2\mu s \quad T_a \approx 4.365\mu s$
  - $B \approx 1.45T \rightarrow$  Storage ring radius  $\approx 7.112m$
  - $\gamma \approx 29.3 \rightarrow p_u \approx 3.09 \text{ GeV}/c$
- “Magic”  $\gamma = \sqrt{\frac{a}{1+a}} \approx 29.3 \rightarrow$  Minimizes the  $\vec{B} \times \vec{E}$  term

$$\omega_a = -\frac{mc}{e} [a_u \vec{B} - (a_u - \frac{\gamma^2 - 1}{\gamma}) \vec{E}]$$

With homogeneous  $\vec{B}$ , use quadrupole  $\vec{E}$  to focus and store beam

Spin Precession with  $\vec{B}$  and  $\vec{E}$





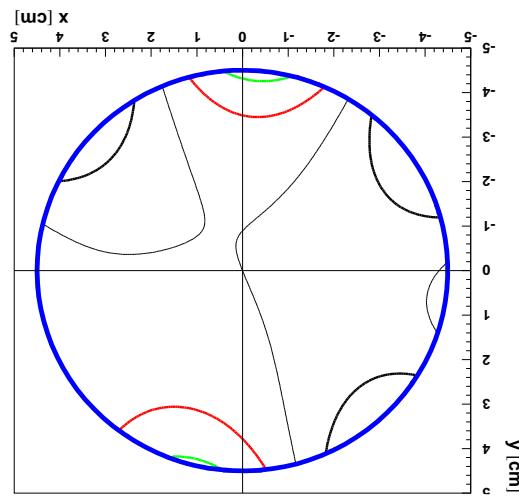
Determination of Average B-field ( $\omega^d$ ) over Muon Ensemble

Goal: Get the average precession frequency of the NMR protons in the same average B-field seen by stored muons.

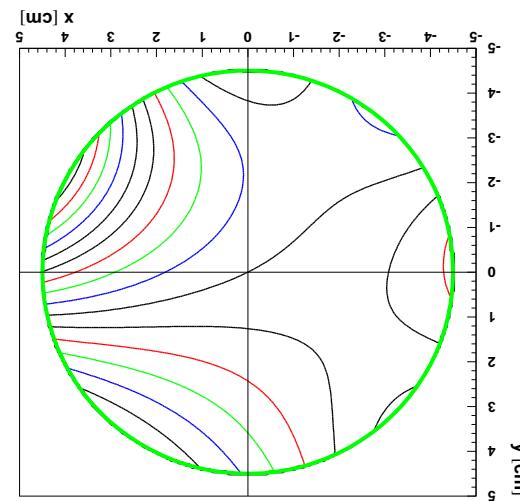
### Mapping of B-field

- Complete B-Field map of storage region (in vacuum)
- Every 3-4 days
- Beam trolley with  $^{17}\text{NMR}$  probes
- Continuous monitor of B-field with  $\approx 150$  fixed probes
- Two largely independent analyses of the B-field data,
- agree well

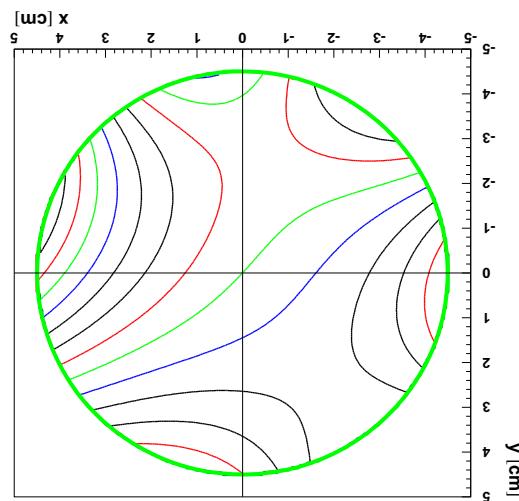
**2000 run**



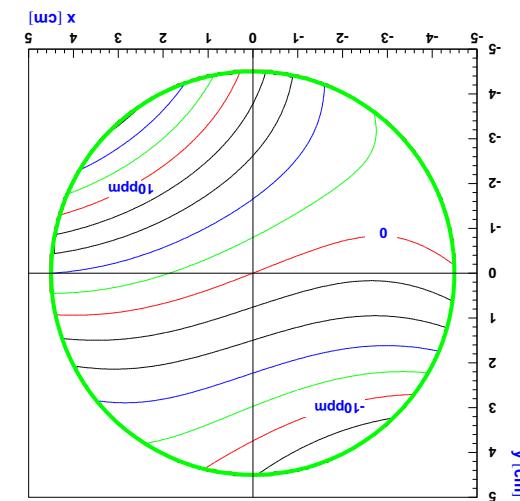
**1999 run**



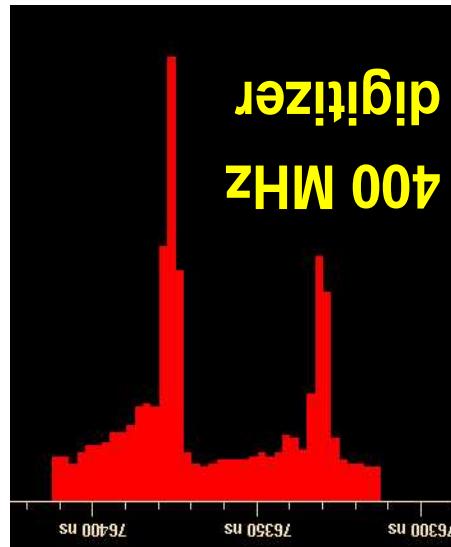
**1998 run**



**1997 run**



(Azimuthal Average, 1 ppm contours, except '97)  
Magnetic Field Uniformity



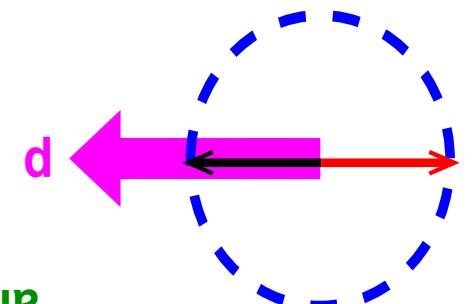
Measures Energy  
and time

Sci-Fi Calorimeter  
module

muon spin

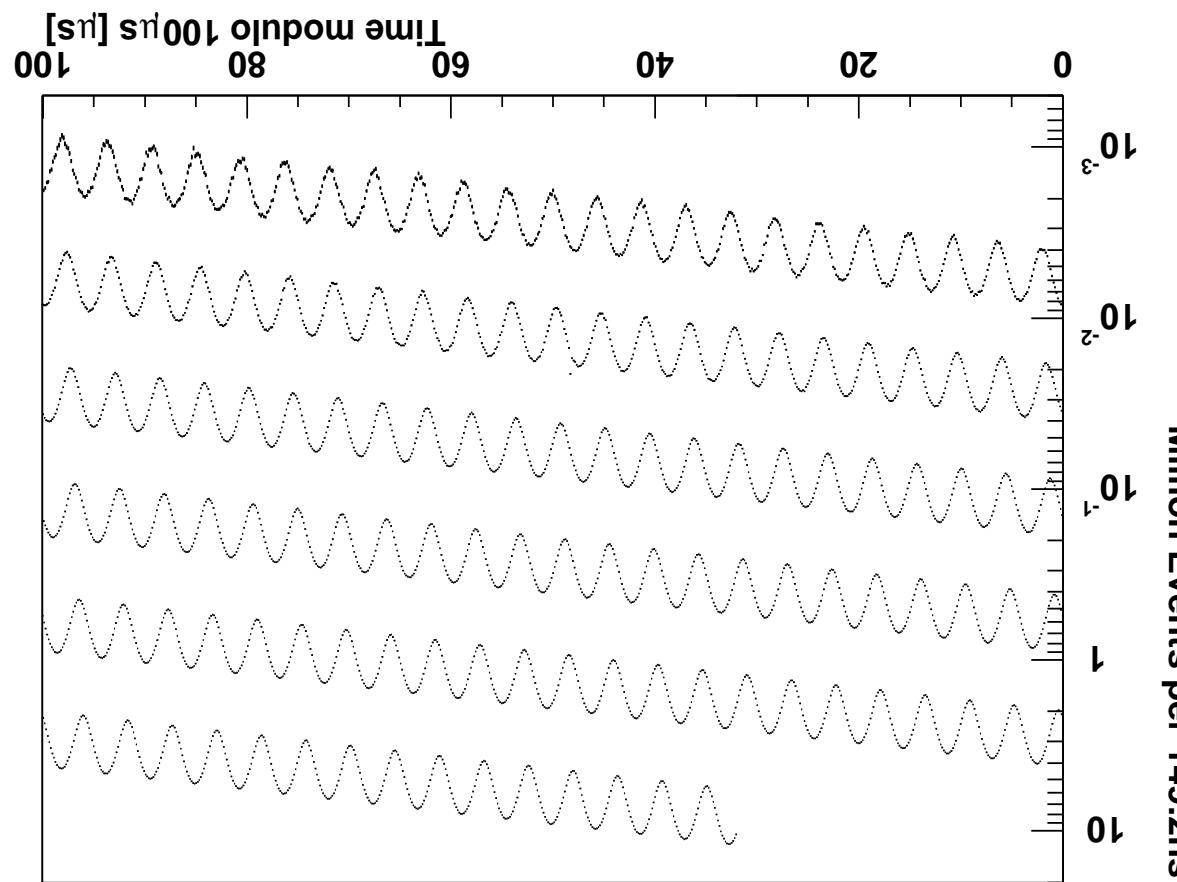
muon momentum

high energy e  
spin backward, less  
high energy e  
spin forward, more

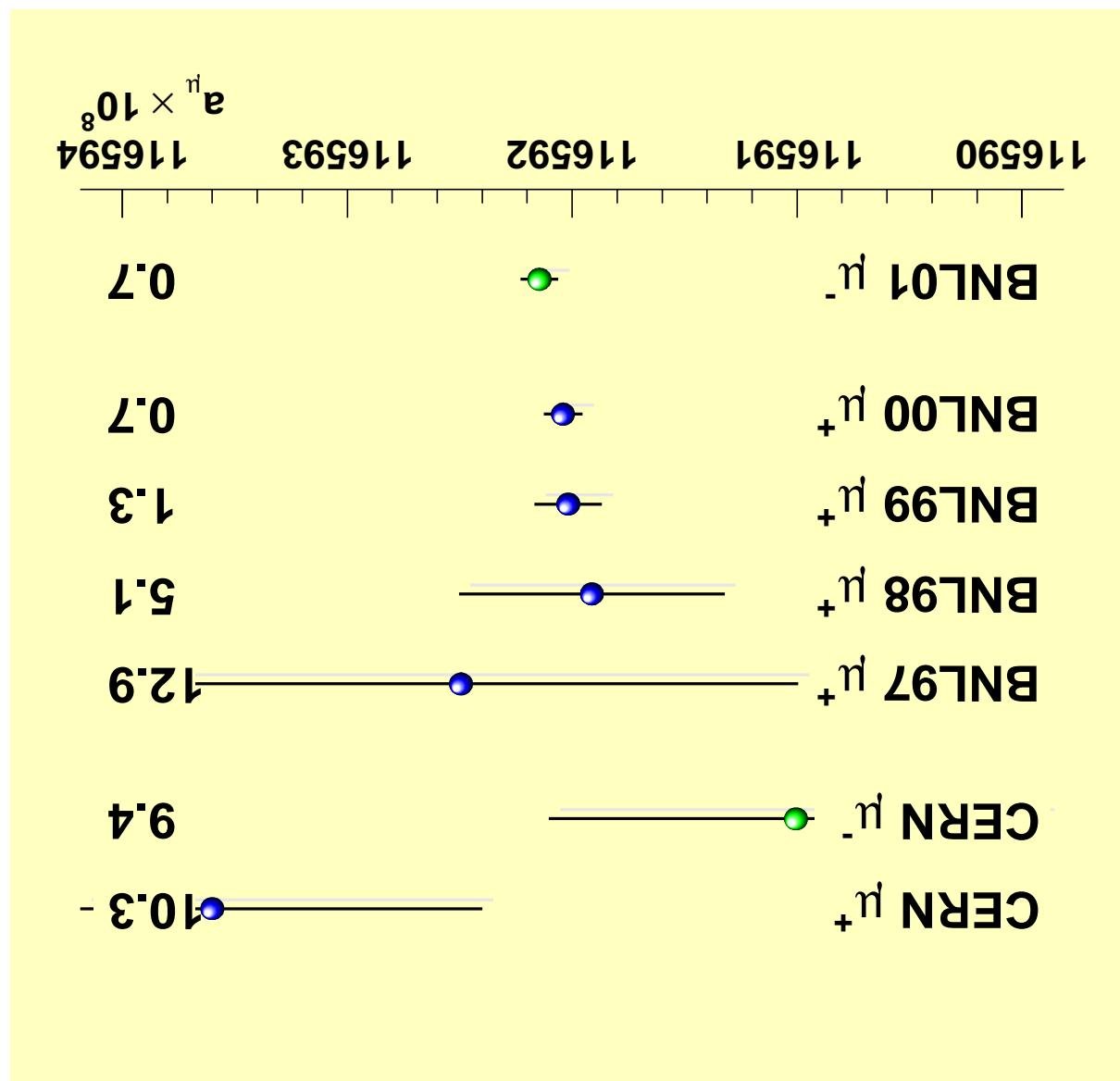


$$N(t) = N_0 e^{-\lambda t} [1 + A \sin(\omega_a t + \phi)]$$

5-parameter function

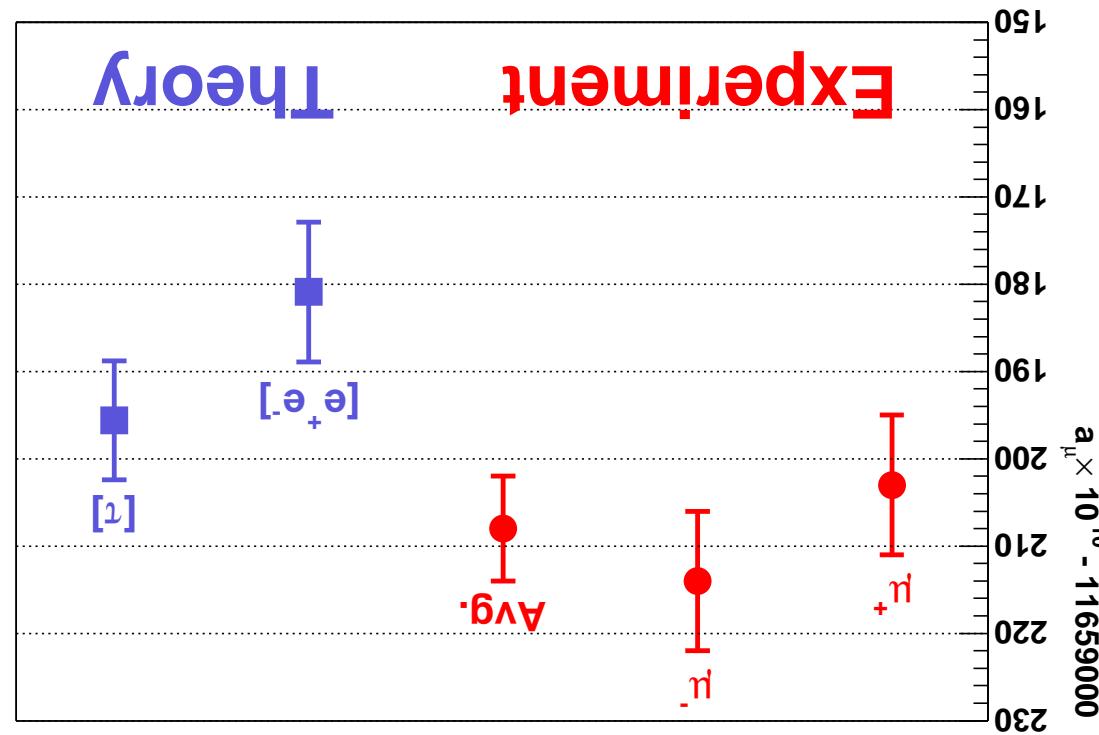


Log plot of 2001  
data,  $E > 2$  GeV  
100 ns segments  
Statistical error:  
 $\approx 0.66$  ppm



$$\Delta a_\mu(\tau) = (7.6 \pm 8.9) \times 10^{-10} \quad 0.9 \text{ s.d.}$$

$$\Delta a_\mu(ee) = (23.9 \pm 9.9) \times 10^{-10} \quad 2.7 \text{ s.d.}$$



Year	B-field ( $w_p^a$ )	Spin ( $w_a$ )	Sytematic	Total	Total	$\sigma_{stat}$	$\sigma_{sys}$	(ppm)	(ppm)	(ppm)	(ppm)
1999	0.4	0.3	0.5	1.3	1.4	0.27	0.39	0.31	0.17	0.24	0.24
2000	0.24	0.24	0.31	0.62	0.7	0.62	0.39	0.21	0.17	0.24	0.24
2001	0.17	0.17	0.21	0.66	0.7	0.27	0.39	0.31	0.17	0.24	0.24
											0.46
											0.5

Errors vs. Time

- increase statistical sample by x9
- reduce systematic error by x2

To get this reduction in overall uncertainty:

- Statistical uncertainty: 0.14 ppm
- Systematic uncertainty: 0.14 ppm

$$\text{Goal: } \frac{\delta a_\mu}{a_\mu} = 0.20 \text{ ppm}$$

- Statistical uncertainty (1999, 2000, 2001 data sets): 0.46 ppm  
(0.17 ppm B-field, 0.21 ppm precession frequency)
- Systematic uncertainty (2001 data set): 0.27 ppm

$$\text{Current: } \frac{\delta a_\mu}{a_\mu} = 0.5 \text{ ppm}$$

Plans for an Upgraded g-2 Experiment at BNL

- increase statistical sample by x200
- reduce systematic error by  $\times 7$

To get factor of 10 reduction in overall uncertainty:

- Statistical uncertainty: 0.03 ppm
- Systematic uncertainty: 0.04 ppm

$$\text{Goal: } \frac{\delta a_\mu}{a_\mu} = 0.05 \text{ ppm}$$

- Statistical uncertainty (1999, 2000, 2001 data sets): 0.42 ppm (0.17 ppm B-field, 0.21 ppm precession frequency)
- Systematic uncertainty (2001 data set): 0.27 ppm

$$\text{Current: } \frac{\delta a_\mu}{a_\mu} = 0.5 \text{ ppm}$$

## Facility

Plans for a NEW g-2 Experiment at a Future High-flux

We will assume the magic gamma approach for now....

- Build new ring? e.g. idea of Farley et al. to go to large momentum, use RF to compress particles onto same orbits- gain because  $\frac{d\omega}{\omega} \sim \frac{1}{T}$
- Keep BNL approach, move ring to new high flux facility?

## Ring Design

Pulsed beam: high pulse rate desirable

weeks run time

With 4(easy)×8(harder)×10(proton intensity)×3(8 GeV), need 50

- Li lens, ×2
- Redesign inflector with larger aperture, >×2
- Space matching of beamline to ring, ×2
- Longer pion → muon decay beamline + better phase

More costly and/or difficult options

- ( $\mu$ )
- Backward muon beam to eliminate 'flash', ×1 (5.4 GeV/c)
  - More magnetic quadrupoles in beam line, ×2
  - Open inflector ends to reduce multiple scattering, ×2

Some straightforward improvements:

×200 total BNL data set

For 0.05 ppm (0.03 stat., 0.04 syst.)

Statistics Increase Needed for ×10 Reduction in Error

- Maximum flux of 3.1 GeV/c muons with  $\frac{d}{\Delta d} > .3\%$
- Vertical beam divergence  $< 3 \text{ mrad}$
- Horizontal beam divergence  $< 5 \text{ mrad}$
- Pulsed beam (width  $< 20 \text{ ns}$ )
- High pulse repetition rate, minimum 1 ms between pulses
- Reduces pileup issues in detector system
- Reduces demands on primary target
- May be disadvantage in case of having to pulse Li lens)

## Beam Requirements

2001 improvements: refined calibrations, improved trolley position  
 trolley calibration  
 2000 improvements: New Infector with 5x less fringe field, Better  
 eddy currents, time-varying stray fields.  
 † Higher multipoles, trolley temperature and voltage response, kicker

Source	(ppm)	1999	2000	2001	NMR Absolute Calib.	0.05	0.05	0.05	Calibration of trolley probes	0.20	0.15	0.09	Trolley measurements of $B_0$	0.10	0.10	0.05	Fixed probe interpolation	0.15	0.10	0.07	Uncertainty in $\mu$ -distribution	0.12	0.03	0.03	Others†	0.15	0.10	0.10	Infector Fringe Field	0.20	-	-	Total systematic error on $w_p$	0.4	0.24	0.17
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Systematic Errors on B-field ( $< \omega_p >$ )

Systematic Errors on  $\langle \omega^p \rangle$ : Standard NMR Probe Calib.

Goal: 0.02 ppm

Now: 0.05 ppm

- Spherical probe: corrections made for material to normalize to free proton

Limited by uncertainty in diamagnetic susceptibility of  $H_2O$ - im-

prove measurement.

- Go to  $^3He$  probe?

Low susceptibility and hence low error; also wide temp. range

- Improve knowledge of trolley position
- Improve  $B$  homogeneity  $\rightarrow$  improve NMR probe performance, reduce dependence on trolley position
- $\times 2$  smaller storage aperture radius or larger extent for trolley map full storage region
- Control temperature, electronics stability to greater degree

Goal: 0.015 ppm

Now: 0.10 ppm

Systematic Errors on  $\langle \omega^p \rangle$ : Trolley Measurements of  $B_0$

- Reduce positioning error on trolley NMR probes
- Reduce inhomogeneities of B-field in calib. region
- Give trolley probes exactly same geometry as standard probe, place in exactly same field position for calibration
- During calibration:

Goal: 0.015 ppm

Now: 0.05 ppm

Systematic Errors on  $\langle \omega^p \rangle$ : Trolley Probe Calibrations

- Place probes closer to center of storage region and away from pole tips, esp. pole tip edges → better linear relation to change in probes and change in  $B$ .
- Increase number of fixed probes to improve sampling of volume of storage region e.g. Improve stability of ambient temperature
- Reduce drift of  $B$ -field due to temperature change

Future: 0.010 ppm

Now: 0.07 ppm

Systematic Errors on  $\langle \omega^p \rangle$ : Fixed probe interpolation

rect

- Install Faraday effect monitor of eddy currents, measure and cor-

Currently error < 0.1 ppm at 20  $\mu$ s

Kicker eddy currents

- Improve cooling and temp. stability of electronics

Trolley temperature stability

Systematic Errors on  $\langle \omega^p \rangle$ :

- Improved traceback and fiber monitor performance
- Reduce ‘flash’: eliminate pions (and protons if possible) - longer beam line, backward muons, or muon accumulator uncertainty.
- Improved  $B$  homogeneity reduces sensitivity to muon distribution
- Narrower bunch time ( $< 10$  ns?)  $\leftarrow$  better fast rotation analysis.
- Movable collimators to map distribution

Goal: 0.01 ppm

Now: 0.03 ppm

Systematic Errors on  $\langle \omega^p \rangle$ : Uncertainty in muon distribution

## study

- Improve storage region homogeneity- passive + active shimming
- Improves NMR performance
- Reduces error in  $B$  due to muon dist., uncertainty in losses,
- Reduce standard probe calibration uncertainty
- Reduce uncertainty trolley position
- Improve cooling temperature stability of trolley probes, electronics
- Measure kicker eddy currents and correct (in vacuum)
- Increase number and improve positioning of fixed probes
- Precess stored protons, electrons, heavy ions  $\leftarrow \langle B \rangle$
- Reduce storage region radius by  $\times 2$  (gap same)
- Reduces errors from: muon dist uncertainty, fixed probe interpo-  
lation, easier to shim and map reduced volume
- $\times 4$  syst error reduction quite doable,  $\times 10$  possibility with extensive

## Summary of B-field Improvements

Sweeper magnet to eliminate AGS background

New in 2000

Source	(ppm)	1999	2000	2001	Systematic Errors on Precession Frequency ( $\langle \omega^a \rangle$ )	Total systematic error on $\omega^a$	0.3	0.31	0.21
AGS Background	0.10	0.01	0.01		AGS Background	0.10	0.10	0.09	0.09
Pile-Up	0.13	0.13	0.08		Pile-Up	0.10	0.02	0.02	0.10
Lost Muons	0.10	0.10	0.09		Lost Muons	0.10	0.10	0.09	0.10
Timing Shifts	0.10	0.02	0.02		Timing Shifts	0.10	0.02	0.02	0.10
E-field and vertical $\beta$ -motion	0.08	0.03	0.06		E-field and vertical $\beta$ -motion	0.08	0.03	0.06	0.07
Fitting Method / Binning	0.07	0.06	0.06		Fitting Method / Binning	0.07	0.06	0.06	0.07
Cohrent Betatron Oscillation	0.05	0.21	0.07		Cohrent Betatron Oscillation	0.05	0.21	0.07	0.07
Beam debrunching	0.04	0.04	0.04		Beam debrunching	0.04	0.04	0.04	0.04
Detector Gain Changes	0.02	0.13	0.12		Detector Gain Changes	0.02	0.13	0.12	0.12
Total systematic error on $\omega^a$					Total systematic error on $\omega^a$				

Systematic Errors on Precession Frequency ( $\langle \omega^a \rangle$ )

- Small distortions important for high statistics sample.
- Positron pulses overlapping in time (pile-up)
- Coherent betatron oscillations
- Muon losses
- Detector gain stability

$$N(t) = N_0 e^{-\gamma t} [1 + A \sin(\omega_a t + \phi)]$$

5-parameter function

- Increase segmentation in detector/PMT/WFD
- Currently 4 elements/detector are summed before digitization.
- Better control of gains and pulse shapes of individual detector elements (crucial to pileup modeling)
- Use hodoscope in front of detectors to tag multiple particles entering calorimeter
- Reduce beam rate, increase pulse repetition rate, rate x pulse rate=fixed
- Histogram energy versus time in detectors- get rid of pileup completely ("Q" method)

## Improve Control of Pileup

- Improve orbit kick to reduce CBO amplitude
- Increase the size of inflector aperture
- Vary beam scraping time
- Sextupole E or B field to damp out CBO
- Active RF to reduce CBO amplitude.
- Choose n: CBO resonance frequencies far from  $\omega_a$

Future:  $\omega_a(CBO) = 0.015 \text{ ppm}$

Currently:  $\omega_a(CBO) = 0.07 \text{ ppm}$

Future run: Plans to reduce  $\omega_a(CBO)$

- Improved simulation of losses
- Reduce muon loss rate- new scraping techniques increased losses
- Moveable apertures distributed around ring to probe for
- Increase ring coverage of muon loss monitors

### Ways to Reduce Error

- Contribution to  $\omega_a = 0.10 \text{ ppm}$
- Which differs from average
- Possible problem: Lost muons could have spin phase
- Distortion of  $N(t)$  has minimal effect on value of  $\omega_a$
- Lost muons monitored by scintillator elements at 11 detector stations.
- Losses  $\approx 1\%$  per  $\tau_u$  at  $30 \mu\text{s}$ ,  $0.1\%$  late times
- Minimized by 'scraping' beam at early times,  $\approx 0 - 10 \mu\text{s}$

### Muon Losses

- Reduction of the ‘flash’ associated with particle injection (use longer beam line, muon accumulator, or backward-decay muons)
- Gate on PMT sooner (gain settles sooner), or eliminate gate backward muons): calibration fits more reliable
- Reduce background (longer beam line, muon accumulator or backward muons)
- Gate on PMT sooner (gain settles sooner), or eliminate gate backward muons)

## FUTURE IMPROVEMENTS

- $\sigma_{\omega^a}(\text{gain}) = 0.13 \text{ ppm (1999)}, 0.12 \text{ ppm (2000)}, 0.12 \text{ ppm (2001)}$
- Stabilized over 10 muon lifetimes.
- Affected by background levels, rates, PMT gate-on time, ‘island’ effect
- Average positron energy vs. time

## Detector Gain Stability

- $a_u^{\text{exp}}(\text{exp})$  agrees with  $a_u^{\text{exp}}(\text{exp})$  (CPT) theory value
- Experimentally,  $\frac{a_u}{\langle a_u \rangle} = 0.5$  ppm is statistics limited and approaches original goal of 0.35 ppm
- Combined  $a_u^{\pm}$  differs 2.7 s.d. ( $e^+_e^-$ ) or 0.9 s.d. ( $\tau$ ) from  $e^+_e^-$

From recent published data

- $a_u$  sensitive to the presence of new particles beyond the standard model, e.g. SUSY especially with large  $\tan(\beta)$
- discovery potential if there is disagreement with SM constraints on new models if there is agreement with SM
- if LHC sees SUSY particle, then  $a_u$  will give  $\tan(\beta)$

## Conclusions

- Improvements in errors of both exp't. and theory are highly desirable as a test of the SM, and are quite feasible.
- New  $e^+e^-$  data coming: VEPP upgrade to 2 GeV, radiative return data from DAPHNE, SLAC, Cornell....
- $e^+e^-$  vs.  $\tau$  discrepancy, light-on-light calculations, continue to get a lot of attention from theorists
- A proposal has recently been approved by BNL PAC for another data run, at x5 intensity, which would enable better than a x2 reduction in uncertainty and a more definitive comparison with theory.
- Please let us know if you are interested in joining the effort!

## Outlook

## A g-2 Experiment at a Future High-flux Facility

Outlook (Continued)

- Proposed muon run challenging but doable:
  - x200 more data- quite feasible
  - x<sub>7</sub> improvement in systematic uncertainty- x3-4 already in sight,
  - remainder requires detailed studies and development (Move current ring or build new?)
  - If theory is good enough, excellent physics potential.
  - Theory has improved by x5 in last 15 years...another possible factor of two is in sight... in the future, who can tell?
- Same type of new physics may lead to non-zero muon EDM: efforts under way to develop an experiment to measure muon (and deuteron) EDM using the storage ring technique
  - Same type of new physics may lead to non-zero muon EDM: effort of two is in sight... in the future, who can tell?
  - Same type of new physics may lead to non-zero muon EDM: efforts under way to develop an experiment to measure muon (and deuteron) EDM using the storage ring technique

- Maximum flux of  $3.1 \text{ GeV}/c$  muons with  $\frac{d}{dp} < .3\%$
- muons from forward pion ( $3.1 \text{ GeV}/c$ ) decays, or from backward pion ( $5.4 \text{ GeV}/c$ ) decays
- Vertical beam divergence  $< 3 \text{ mrad}$
- Horizontal beam divergence  $< 5 \text{ mrad}$
- Pulsed beam (width  $< 20 \text{ ns}$ ), high repetition rate, minimum 1 ms between pulses
  - Reduces pileup issues in detector system
  - Reduces demands on primary target

## Beam Requirements